Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica

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Received 3 June 2004; revised 16 July 2004; accepted 26 August 2004; published 22 September 2004.

[1] Ice velocities derived from five Landsat 7 images acquired between January 2000 and February 2003 show a two- to six-fold increase in centerline speed of four glaciers flowing into the now-collapsed section of the Larsen B Ice Shelf. Satellite laser altimetry from ICESat indicates the surface of Hektoria Glacier lowered by up to 38 ± 6 m in a six-month period beginning one year after the break-up in March 2002. Smaller elevation losses are observed for Crane and Jorum glaciers over a later 5-month period. Two glaciers south of the collapse area, Flask and Leppard, show little change in speed or elevation. Seasonal variations in speed preceding the large post-collapse velocity increases suggest that both summer melt percolation and changes in the stress field due to shelf removal play a major role in glacier dynamics. *INDEX TERMS:* 1640 Global Change: Remote sensing; 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827). **Citation:** Scambos, T. A., J. A. Bohlander, C. A. Shuman, and P. Skvarca (2004), Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica, *Geophys. Res. Lett.*, *31*, L18402, doi:10.1029/2004GL020670.

1. Background and Previous Observations

[2] Floating ice shelves are responding rapidly to climate warming in the Antarctic Peninsula. Over the past half-century, mean air temperatures there have increased by 2 to 4°C [*King and Comiso*, 2003; *Skvarca et al.*, 1999] and in the past 30 years ice shelves in the region have decreased in area by >13,500 km^2 [*Vaughan and Doake*, 1996; *Scambos et al.*, 2003]. In three cases large areas have collapsed suddenly: the Larsen A in January 1995 (1600 km^2); Wilkins in March 1998 (1100 km^2), and the Larsen B in February–March, 2002 (3200 km^2).

[3] Air temperature increases in the 1990s led to longer melt seasons and an increase in melt pond extent on the northernmost ice shelves [*Fahnestock et al.*, 2002]. In the same period, ocean temperatures in the Weddell Sea rose, possibly increasing the rate of basal melting of the Larsen Ice Shelf and thereby contributing to collapse [*Shepherd et al.*, 2003]. However, both Larsen collapse events occurred during record warm air temperatures, when surface melt season length and melt pond extent reached new maxima. Areas with melt ponds disintegrated; adjacent areas with few to none remained. This link between climate warming, melt ponding, and ice shelf collapse prompted the proposal of a melt-enhanced fracture mechanism as the main cause of shelf disintegration [*Scambos et al.*, 2000].

[4] Ice shelf removal has been tied to potential glacier flow increases [*Thomas et al.*, 1979]. The presence of a shelf provides 'backstress', or longitudinal compressive force, if a mechanical connection exists between the shelf ice and surrounding land areas, ice rises, or islands. However, some models of ice sheet flow show little effect of shelf removal [*Hindmarsh*, 1996]. The magnitude of this effect is critical to understanding ice sheet mass balance and sea level changes under projected warming conditions.

[5] Melt percolation may also affect the force balance of glaciers. This too has a history in ice mechanics theory [*Weertman*, 1973], and recent observations have placed the discussion in the context of climate change. Measurements of surface flow speed on ice sheets and glaciers suggest that summer meltwater can descend via crevasses to the bed, seasonally reducing basal stress and increasing flow speed by up to 25%, even when the glaciers contain ice well below freezing [*Zwally et al.*, 2002a; *Boon and Sharp*, 2003].

[6] Following the collapse of Larsen A Ice Shelf in January 1995, interferometric synthetic aperture radar (InSAR) revealed that two of its tributary glaciers increased in speed by up to 3-fold [*Rott et al.*, 2002]. The InSAR image pairs were acquired in late 1995 and late 1999. Speed increased throughout the glaciers, but along-flow speed profiles for Drygalski Glacier indicated an abrupt increase in speed gradient in the lowest parts of the glacier trunk. The location of this speed profile 'kink' moved upstream by 8 km in the four-year span. Above the kink, flow speed increased, but more uniformly. The authors note that acceleration may have begun prior to the first survey.

[7] Photographs of the Drygalski Glacier valley walls in early 2002 showed remnant ice ridges ('ice terraces') 20 to 40 m above the glacier surface, indicating a substantial surface lowering [*De Angelis and Skvarca*, 2003]. Additional satellite image evidence suggested rapid speed increases (surging) for other glaciers flowing into the Larsen A embayment. Here we use speed and elevation data acquired closer in time to a shelf collapse event to study the effects of shelf removal and climate warming on glaciers in more detail.

2. Speed and Elevation Measurements

[8] Five satellite images spanning the period of Larsen B Ice Shelf retreat and collapse are used to map the velocity of six glaciers draining into the Larsen B embayment. Landsat 7 Enhanced Thematic Mapper (ETM+) images from 27 January 2000, 06 December 2001, 06 April 2002, 18 December 2002, and 20 February 2003, were

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0094-8276/04/2004GL020670$05.00

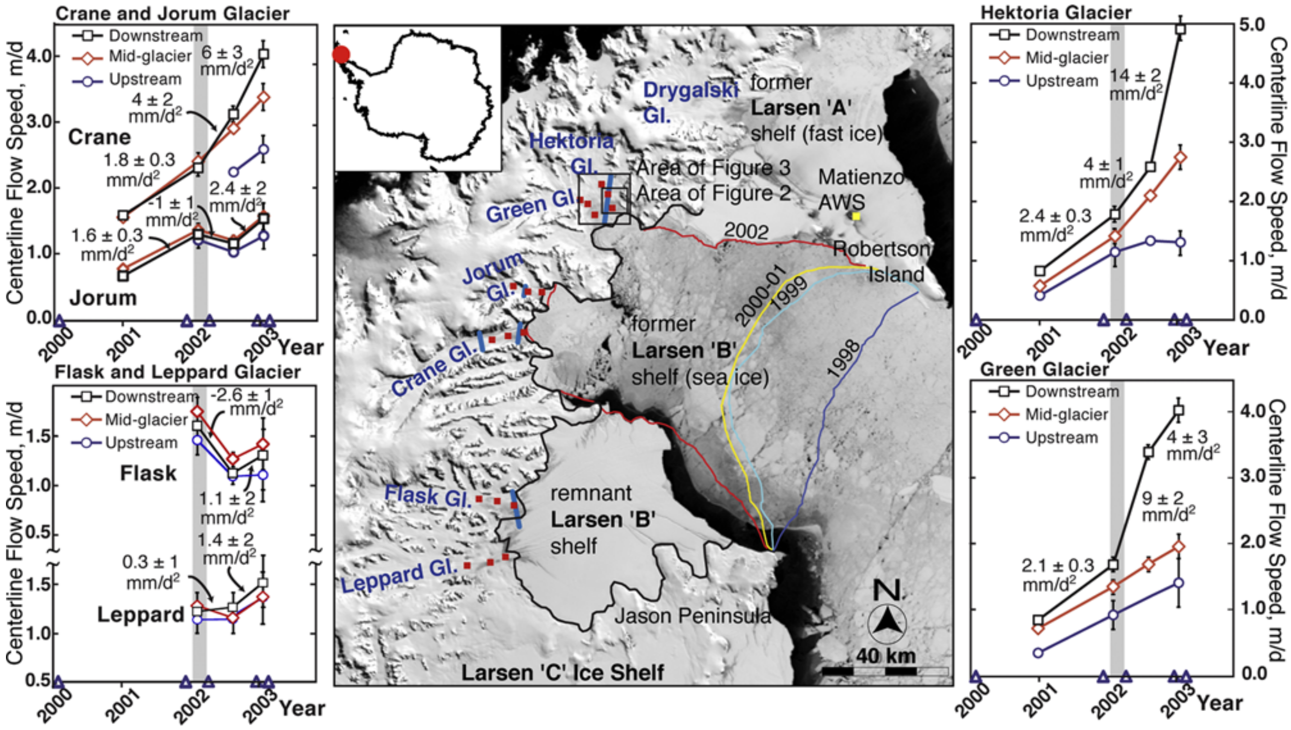

Figure 1. Center panel: MODIS image from 1 November 2003 of the study area with April ice shelf extents and the grounding line (black [*Rack and Rott*, 2004]) for the Larsen B Ice Shelf between 1998 and 2002. Red boxes are speed measurement sites along lower glacier centerlines. Short blue lines indicate locations of ICESat laser altimetry ground tracks over glacier trunks. Surrounding graphs: centerline ice speeds and downstream site accelerations for six glaciers. Landsat 7 image acquisition dates are shown as triangles on the *x*-axes. Grey bars represent the Feb.–Mar. 2002 shelf collapse event.

used in an image feature-tracking algorithm [*Scambos et al.*, 1992] to gather ice motion data along selected flow centerline points in the lowest 10 to 12 km of the glaciers. We mapped four glaciers feeding the now-empty northern shelf embayment (Hektoria, Green, Jorum, and Crane) and two glaciers (Flask and Leppard) flowing into the remaining southern ice shelf areas (Figure 1). The images are used in sequential pairs, permitting some seasonal resolution of ice flow variations.

[9] Errors from the image feature-tracking algorithm come from two sources: image mis-registration; and noise in the correlation matches of image 'chip' pairs. For the Larsen B images, mountain ridges allowed co-registration to within a pixel (15 meters for ETM+ band 8). Noise in adjacent correlation matches for the ice motion vectors is approximately 0.25 to 0.5 pixels. The reported centerline values (Figure 1) are averages of 5 to 50 vectors within a few hundred meters of the selected site. In some cases thin clouds or saturation of the band 8 data forced different approaches, either using unsaturated bands (band 3 and 4 of ETM+) or in one case manually tracking features. Errors shown in the graphs are based on displacement measurement errors of ±20 meters (1.33 band 8 pixels) to ±40 meters (where other methods were used).

[10] The first image pair spans summer and winter periods before 2002, so the derived ice motion measurements approximate the average flow speed just prior to ice shelf collapse. The second image pair spans the period of the March 2002 Larsen B shelf collapse, including the warmest summer and most extensive melt season on record at the Matienzo automated weather station (AWS). Mean summer (December–February) air temperature, MST, was +1.3° [*Skvarca et al.*, 2004]. Glacier speed increased by up to 80% for the four northern glaciers, with little variation along the centerlines.

[11] The third sequential image pair covers the winter period following collapse. Glaciers south of the collapse area, Flask and Leppard, show deceleration or no significant change. However, glaciers draining into the collapsed shelf area accelerated significantly, particularly where retreat reached the grounding line prior to the image period, i.e., for Hektoria and Green glaciers. Speed gradient in the lower parts of these glaciers also increased greatly. The pattern is amplified in the last image pair, which spans most of the summer of 2003. This summer was much cooler than the previous one (MST −1.2°C), with much less melt, and speed changes for Flask Glacier were small.

[12] At both Jorum and Crane glaciers small sections of shelf ice remained throughout the Landsat image series. For Jorum, the 2002 winter image pair indicates a decrease in flow speed, uniform throughout the lower trunk, though speeds are still greater than the pre-collapse mean. In the last image pair period, both glaciers develop an increased speed gradient in their lower trunk. At this point, the remaining shelf was <2 km along the centerline for both glaciers.